THE DISTRIBUTION OF MAXIMUM FLOODS.[1]

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SYNOPSIS.—(1) The records of both American and European rivers show an average of 7 to 10 great floods per century.

(2) Great floods are primarily due to precipitation, and that precipitation, in the form of rain, which produces floods may be of two distinct types, (a) so intense and widely distributed as to produce flooding regardless of antecedent conditions; (b) moderate rains continued intermittently for 8 to 10 days or more with antecedent conditions favorable to a high run-off.

(3) There does not appear to be an orderly progression in the magnitude of floods with the lapse of years; that is to say, the absolute maximum flood of any 100-year period is not necessarily greater than the absolute maximum flood for the preceding 100 years.

(4) The magnitude of great floods with respect to the average annual flood, seems to increase in a geometrical progression but apparently wholly regardless of the flow of time.

(5) Great floods like great rainfalls are essentially a local phenomenon even for the same stream.

INTRODUCTION.

There is usually for each large stream a fairly well-defined flood season depending quite largely upon the climatic conditions over its watershed. The magnitude of the annual flood is clearly associated with the varying climatic conditions experienced, especially the distribution and intensity of the rainfall over the catchment basin. At times other climatic factors, particularly the temperature distribution, contribute to the magnitude of the annual floods. Floods greater than the average by a fixed amount I have designated as "maximum floods." In the course of years, however, there comes a maximum flood much greater than the average, a flood that is, more or less, epoch making in the region through which the stream flows, and this flood has been designated as the "absolute maximum flood." The object of this paper will be to make a statistical study of the distribution in time and space of maximum floods.

MATERIAL AVAILABLE.

Systematic gagings of the larger rivers of the United States were begun in the early seventies by the U. S. Signal Service (now Weather Bureau), although the U. S. Engineers in charge of river improvements on navigable streams began a few years earlier to gage a few of the larger rivers as an effective aid to improvement work at various points thereon. The object of the Signal Service was different, however, viz, to issue warnings of dangerous floods.

The U. S. Geological Survey began its work of stream gaging in the late eighties and organized a division to oversee the work known as the Irrigation Survey. This branch of the Survey later formed the nucleus of the present Reclamation Service. In the beginning, the Geological Survey was interested in discovering the quantity of water available for irrigation. In recent years it was and is now concerned chiefly in determining the water resources, both surface and underground, in practically all parts of the country. There are, therefore, three of the executive departments of the Government—Agriculture, War, and Interior—directly concerned in the gaging of streams, and one or two others, more or less, indirectly concerned.

The period of continuous observations on this continent is short. On the Mississippi and Ohio it is about 45 years, but for a few places thereon, such as St. Louis, Mo., Cincinnati, Ohio, and Pittsburgh, Pa., as many as 65 years of continuous observations are available. In addition to the above, two New England rivers, the Connecticut at Hartford, Conn., and the Merrimac at Lawrence, Mass., have been gaged for more than half a century. Permanent records of high water were made at Hartford, and these have been referred to the zero of the present gage at that place, hence, a record of the occurrence of floods previous to the beginning of the regular gagings is available for that station and at a few other points throughout the country. The Hartford record, however, is by far the longest, extending as it does over a span of about 300 years.

In the middle Mississippi Valley the record goes back to the 1844 flood, and there is evidence of a previous great flood in 1785, although the level of that flood has never been definitely fixed. Apparently it was in the neighborhood of 42 feet on the present St. Louis gage. The U. S. Engineers, on the authority of the late Dr. Engleman, give it as 42.0? feet.

THE CAUSE OF FLOODS.

Broadly speaking, it may be said that the precipitation, having due regard for its intensity, duration, and geographic distribution, is the sole cause of the rise and maintenance of floods of whatever magnitude. There are of course important modifying factors, some of which tend to increase, some to diminish, flood flow; hence, the occurrence of floods of different magnitude for the same season in different years. If the arithmetical mean of the annual floods for a number of years be computed, an expression is obtained which represents the average annual flood. Such an expression has its advantages for the purpose of discussion but is, otherwise, without special significance. The average flood is not necessarily the one which happens with the greatest frequency. When the amount of rain which falls is sufficient to raise ground storage to a high level and thus to saturate the soil, or when a warm spell sets in with rain at a time when a blanket of snow is still on the ground the surface run-off becomes excessive and floods of greater or less magnitude—maximum floods—result. These floods occur irregularly with the lapse of time and the fluctuations of climate. In the course of a few years, or it may be many years, some one of these maximum floods overtops all previously recorded floods, and this flood is known as the absolute maximum for the period in question. Naturally it is of tremendous importance, economically, to determine whether the absolute maximum has been reached and if not what will be its magnitude when it does come.

It can not be too strongly emphasized that the occurrence of the absolute maximum flood is usually conditioned upon the synchronism of certain climatic events which in themselves have no fixed law of occurrence. Very intense rainstorms are seldom long continued and of great extent. The heavy summer showers that occur in the United States being limited in area may cause an extraordinary flood in a small watershed, and doubtless many such floods occur in some part of the country annually. These extreme floods in small streams are completely absorbed as soon as they reach the trunk stream.

[1] Read before the American Meteorological Society at New York, Jan. 3, 1920.

In winter, spring, and early June the occurrence of floods is quite closely related to the quantity of rain which falls; in summer, however, owing to the demands of vegetation and the loss by evaporation, floods are infrequent even with rainfall above the normal. In a typical eastern watershed the run-off may and often does sink to 5 or 6 per cent of the precipitation; hence, it is only when rain is substantially continuous for a day or so that there is any flood menace in summer, except for certain restricted districts to be named in the next paragraph.

North of the 37th parallel the movement of rainstorms in summer is usually too rapid to permit heavy rains on two consecutive days. Under the conditions which prevail in the east Gulf and south Atlantic States, however, a slow-moving cyclonic storm of tropical, or extra-tropical, origin may cause floods in the warm season regardless of the soil and vegetal conditions.

TABLE 1.—*Absolute maximum and average annual flood on 45 rivers of the United States with ratio, absolute maximum to average maximum.*

River.	Station.	Number of years.	Absolute maximum.	Date.		Mean of annual floods.	Ratio absolute to average.
				Year.	Month.		
Atlantic (north).			*Feet.*			*Feet.*	
Connecticut	Hartford	79	29.8	1854	May	20.9	1.43
Merrimac	Lawrence	58	29.7	1896	March	20.2	1.47
Hudson	Albany	30	22.4	1913	....do	15.6	1.44
Delaware	Phillipsburg	25	35.9	1903	October	21.1	1.70
Susquehanna	Wilkes-Barre	22	33.1	1865	March	23.7	1.40
Do	Harrisburg	29	26.8	1889	June	17.2	1.56
Atlantic (south).							
Potomac	Harpers Ferry	28	27.0	1902	March	15.8	1.71
James	Lynchburg	26	33.0	1877	November	13.8	2.39
Roanoke	Weldon	28	60.3	1877	....do	41.2	1.46
Cape Fear	Fayetteville	26	68.7	1908	August	45.2	1.52
Great Pedee	Cheraw	27	44.3	1908	....do	33.9	1.31
Cat-Wateree	Camden	27	40.4	1916	July	30.7	1.31
Congaree	Columbia	24	35.8	1908	August	20.7	1.73
Savannah	Augusta	43	38.8	1908	....do	30.9	1.26
Oconee	Milledgeville	15	33.8	1912	March	24.3	1.39
Ocmulgee	Macon	20	24.0	1887	....do	20.0	1.20
East Gulf.							
Flint	Albany	26	32.4	1897	March	21.8	1.49
Chattahoochee	Eufala	26	56.0	1902	....do	39.2	1.43
Alabama	Montgomery	28	59.7	1886	April	40.7	1.47
Tombigbee	Demopolis	26	72.9	1900	....do	54.9	1.33
Black Warrior	Tuscaloosa	28	66.3	1916	July	52.6	1.26
Pascagoula	Merrill	14	27.0	1916	....do	21.5	1.26
Pearl	Columbia	14	27.6	1909	June	21.1	1.31
West Gulf.							
Trinity	Riverside	16	49.7	1908	June	31.3	1.59
Brazos	Waco	19	39.7	1913	December	22.9	1.73
Colorado	Austin	16	34.7	1900	April	14.0	2.48
Guadalupe	Gonzales	15	38.1	1913	December	20.3	1.88
Interior.							
Ohio	Pittsburgh	65	35.5	1907	March	23.8	1.49
	Cincinnati	58	71.1	1884	February	45.1	1.58
	Louisville	46	46.5	1884	....do	27.8	1.67
	Evansville	46	48.4	1913	March	40.6	1.19
Tennessee	Chattanooga	43	58.6	1867	....do	33.9	1.73
Cumberland	Nashville	45	55.3	1882	January	40.8	1.36
Illinois	Peoria	36	27.1	1849		17.7	1.53
Wisconsin	Wausau	9	15.3	1912	July	8.8	1.74
Mississippi	St. Paul	45	19.7	1881	April	11.0	1.79
	La Crosse	46	16.2	1880	June	10.5	1.54
	Dubuque	44	21.7	1880	....do	13.8	1.57
	Davenport	45	19.4	1892	....do	12.3	1.58
	Keokuk	51	19.6	1888	May	14.0	1.40
	Hannibal	40	22.5	1903	June	17.5	1.29
	St. Louis	72	38.0	1844	....do	27.2	1.40
Missouri	Omaha	44	23.8	1881	April	16.0	1.49
	Kansas City	46	38.0	1844	June	21.1	1.80
Arkansas	Little Rock	47	32.6	1844	May	22.2	1.47
Ouachita	Camden	33	46.0	1882	....do	35.7	1.29
Red	Fulton	33	34.8	1882	....do	28.5	1.22
	Shreveport	36	45.7	1882	....do	34.0	1.34
Pacific Coast.							
Columbia	Umatilla	36	34.5	1894	June	21.4	1.61
Snake	Lewiston	25	26.6	1894	....do	15.9	1.67
Willamette	Albany	27	31.3	1903	January	15.6	2.01
Sacramento	Sacramento	26	29.6	1909	....do	24.8	1.19
American	Folsom	21	38.3	1862	....do	17.7	2.16
San Joaquin	Firebaugh	12	13.7	1911	June	10.6	1.29
Colorado	Yuma	12	33.2	1891	February	27.7	1.20
Grand	Grand Junction	11	13.0	1917	June	10.2	1.27
Green	Elgin	12	17.5	1917	....do	12.6	1.39

MEAN ANNUAL FLOOD.

The mean annual flood on 45 rivers in the United States, using the single greatest flood when two or more floods occurred in the same year, has been computed and the results are presented in Table 1. The average length of record is, for rivers of the north Atlantic drainage, 40 years; south Atlantic, 26 years; east Gulf, 23 years; west Gulf, 19 years; Mississippi, 49 years; Ohio, 54 years; Tennessee and Cumberland, 44 years; Missouri, 45 years; Arkansas, Red, and Ouachita, 39 years; Columbia, 36 years; Colorado, 12 years; and California Rivers, 20 years.

The table shows the name of the river, the gaging point, the number of years of observations, the absolute maximum flood, the year and month of occurrence, the mean annual flood and the ratio of the absolute maximum to the average annual flood. Mr. Weston E. Fuller, in his comprehensive paper, Flood Flows[2] computes the ratio of the maximum flood and the 24-hour average rate of flow as determined by discharge measurements for both the maximum and the average annual flood. Inasmuch as discharge measurements, especially for flood flows, are available for but a very short period, this method was not available. Gage heights, as a rule, indicate with sufficient accuracy the relative magnitudes of the recorded floods. There are a very few cases when changes in the cross section of the stream at the gaging point vitiates the results but none such have been used in this discussion. In the Mississippi below Cairo the channel capacity has been altered to such an extent by the building of levees that no method of comparison for different periods is satisfactory.

The usefulness of the ratio absolute maximum to average annual flood may be determined by comparing the results for streams in different parts of the country. While the ratios in the table speak for themselves, I may be permitted to make the following comment:

The agreement in general is better than was expected. It is a reasonable and fairly accurate inference, except in some cases that will be mentioned later, that the absolute maximum flood will be 1.3 to 1.4 or 1.5 times the mean annual flood.

In the group of New England rivers, including two of the longest records available, the ratio is in substantial accord. The only discordant ratio is that for the Delaware River at Phillipsburg. The ratio in this case is 1.70—that is, the absolute maximum flood was 170 per cent of the average annual flood. Other individual cases of a high ratio in other parts of the country are those for the Potomac, James, Congaree, Colorado and other rivers of Texas, the Wisconsin, upper Mississippi, the Missouri at Kansas City, the Willamette of Oregon, and the American of California. It is convenient to consider all of these cases together. The absolute maximum flood on the Delaware occurred in October, 1903, when, owing to heavy rains over the watershed, the river reached the highest stage for upward of 100 years. The average annual flood on the Delaware is relatively low, due to a succession of years of deficient precipitation. It is believed that more observations will materially change the ratio which now obtains. The high ratios which obtain on the Potomac and James are probably due to natural causes. The run-off of both watersheds in unison with the precipitation fluctuates very widely in different years. As a result of light rainfall the average annual flood has a low value. An intense rainstorm, however, owing to the mountainous character of the upper watersheds of both

[2] Transactions American Society of Civil Engineers, 77: 564.

rivers produces a rapid concentration of the run-off and a high flood peak. And since an extraordinary rainfall may occur even in a period of deficient precipitation, a single great rainfall will unduly increase the ratio. The high ratio for the Congaree at Columbia, S. C., is not understood. Since it is not supported by the record of other streams in South Carolina and Georgia, an explanation may be sought in the local conditions at the gaging point—probably by the dam below the gage. The high ratio for Texas rivers, especially the Colorado, is doubtless to be attributed to the climatic features of the State by reason of which the variation in the run-off varies widely from year to year.

The unusually high ratios for the Tennessee at Chattanooga and the Missouri at Kansas City are due in part to the use of an absolute maximum flood which occurred some years prior to the beginning of regular observations. The Tennessee at Chattanooga varies from year to year within rather wide limits as will be shown elsewhere in this paper.

The absolute maximum flood in the Missouri at Kansas City occurred in 1844, and the stage then attained was 3 feet above the highest stage within the period of regular observations. The Kansas River, which joins the Missouri at Kansas City, is a stream of variable flow. It seems probable that the high ratio at Kansas City is due to natural causes coupled with an unusually high absolute flood in 1844.

A high ratio appears for the Wisconsin River at Wausau with only eight years observation, and it is to be noted that the absolute maximum flood at this station was a rain flood in July. Further observations for this station are needed.

The Columbia River presents a case of extremely high water in 1894.[3] At Cascade Locks the previous record of high water was exceeded by 6 feet. As the annual flood of the Columbia is essentially a snow flood, an unusual depth of snow combined with high temperature in the melting season may produce large variations in the annual flood on this river.

As might be expected, small ratios obtain at points along the stream where overflow takes place and the cross section of the stream is greatly increased. Evansville on the Ohio, with a ratio of 1.19, and Hannibal, Mo., on the Mississippi, with a ratio of 1.29, are cases in point.

Eleven of the greatest annual floods on eight of the rivers of the United States having records exceeding 40 consecutive years in length have been classed in the order of magnitude from the absolute maximum down to No. 11 in descending scale, and the ratio of each of the 11 great floods to the average annual flood has been computed and is given in Table 2. The standard deviation for each of the 10 stations has also been computed according to the method of least squares and is given in the table at the top of the column.

The uniformity of the ratios in this table is significant. It is obvious that while there is a general similarity in the ratios for all streams, each has its own individuality conditioned in some measure upon the channel capacity at the gaging point and the variability of the stream. Another interesting point brought out by the table is the small difference between the absolute maximum flood and the flood second in magnitude. In no case is the difference more than a few per cent except on the Missouri at Kansas City, Tennessee at Chattanooga, the Mississippi, at St. Louis, and in a lesser degree the Cumberland at Nashville. As before remarked, the absolute maximum flood at Kansas City, Chattanooga, and St. Louis occurred some years prior to the beginning of regular observations. It may well be that these relatively high ratios approximate the true ratio for periods exceeding a century better than do the others.

TABLE 2.—*Ratios of the 11 great floods to the average flood at the gaging stations named; floods arranged in the order of their magnitude from No. 1 to 11, from records of 40 years and upward.*

[Standard deviation in feet and hundredths at top of each column.]

No. of flood.	River.										Mean.
	Connecticut, at Hartford.	Merrimac, at Lawrence.	Savannah, at Augusta.	Missouri, at Kansas City.	Arkansas, at Little Rock.	Ohio, at Pittsburgh.	Mississippi, at St. Louis.	Cumberland, at Nashville.	Ohio, at Cincinnati.	Tennessee, at Chattanooga.	
	3.69	3.73	3.76	4.13	4.28	4.33	4.58	6.79	7.78	9.26	
1	1.43	1.47	1.27	1.80	1.46	1.46	1.52	1.36	1.37	1.73	1.48
2	1.37	1.43	1.27	1.66	1.28	1.37	1.40	1.24	1.35	1.59	1.39
3	1.30	1.38	1.20	1.43	1.27	1.33	1.32	1.22	1.28	1.54	1.32
4	1.28	1.33	1.16	1.37	1.27	1.29	1.30	1.21	1.26	1.41	1.28
5	1.27	1.31	1.15	1.28	1.25	1.29	1.28	1.21	1.19	1.26	1.24
6	1.26	1.25	1.15	1.27	1.25	1.28	1.28	1.21	1.19	1.25	1.23
7	1.26	1.21	1.14	1.26	1.23	1.26	1.24	1.21	1.18	1.25	1.22
8	1.26	1.20	1.13	1.19	1.22	1.23	1.24	1.19	1.15	1.20	1.20
9	1.23	1.20	1.09	1.18	1.21	1.23	1.21	1.19	1.14	1.20	1.18
10	1.23	1.19	1.08	1.13	1.19	1.21	1.19	1.14	1.13	1.19	1.16
11	1.22	1.16	1.07	1.12	1.18	1.20	1.18	1.14	1.11	1.18	1.15

GREAT FLOODS IN THE UNITED STATES WITHIN HISTORIC TIMES.

The record of great floods in this country covers about 300 years in New England, somewhat less in the Middle Atlantic States, about 125 years in the Mississippi Valley and about 70 years in California.

The greatest flood of record in California occurred on the American River at Folsom City on January 8, 1862. The crest of this flood has been definitely fixed at 38.3 feet on the present gage at Folsom City, 8.3 feet higher than any subsequent record.

The greatest flood in the lower Missouri and the middle Mississippi Valley occurred in June, 1844, and the crest of that flood at Kansas City and St. Louis Mo., was 3.0 and 3.4 feet, respectively, above the highest water since recorded. The 1844 flood seems to have been confined to the western tributaries of the Mississippi south of the Missouri, since its volume alone was not sufficient to cause more than a moderate flood in the Mississippi below St. Louis, Mo.

Six great floods, of over 60 feet on the Cincinnati gage, occurred on the Ohio during the nineteenth century, viz, in 1832, 1847, 1883, 1884, 1897, and 1898. The average interval is 16 years, but there were two intervals of more than double the average and two floods in successive years.

At Pittsburgh two great floods of almost equal magnitude occurred within the nineteenth century, viz, those of February, 1832, and March, 1897, the latter being a shade the higher. It was, however, more or less local to the vicinity of Pittsburgh and flattened out as it passed downstream.

In New England, the greatest flood of record occurred on the Connecticut in 1854 and on the Merrimac in 1896. The last-named was also more or less local to that river; the synchronous flood in the Connecticut was only No. 4 in magnitude.

[3] MONTHLY WEATHER REVIEW, 22:510.

There were 11 great floods in the Connecticut—25.7 feet and over on the Hartford gage—during the Nineteenth century, viz, in 1801, 1807, 1827, 1841, 1843, 1854, 1859, 1862, 1869, 1895, and 1896. The average interval is nine years and the distribution is more uniform than in the Ohio. It is noteworthy as indicating the localization of great floods that in no single year were the great floods concurrent on both the Ohio and the Connecticut.

There were 14 great floods in the Mississippi at St. Louis during the nineteenth century, 32.0 feet or over, as follows: 1811, 1823, 1826, 1828, 1844, 1845, 1851, 1855, 1858 1876, 1881, 1882, 1883, and 1892. The average interval is seven years.

Among the early floods of the nineteenth century that have thus far not been surpassed are the 1862 floods in California, the 1844 floods in Kansas, Missouri, Illinois, and Arkansas, the 1850–51 floods in the Mississippi above St. Louis, and the 1867 flood in the Tennessee above Decatur, Ala.

An examination of the sequence of flood years gives no indication of the existence of a cycle in which great floods are repeated, but shows conclusively, I think, that the dominating control is rainfall, and since there may be one, two, ot even three years of excessive rainfall, it follows that great floods may likewise occur in successive years. The floods of the nineteenth century appear to be grouped in the forties, sixties, eighties, and nineties. The single years of great flood in one part of the country or another were 1801, 1807, 1810, 1811, 1814, 1823, 1824, 1826, 1828, 1832, 1838, 1839, 1841, 1843, 1844, 1845, 1846, 1851, 1855, 1858, 1862, 1865, 1869, 1876, 1877, 1878, 1880, 1881, 1882, 1883, 1884, 1886, 1889, 1891, 1892, 1894, 1897. It is probable that for the first half of the century the list is incomplete. The list contains 37 years, but the interval between the years is not uniform. There seems to have been a minimum of flooding in the fifties, except in the Mississippi Valley, widespread floods in the sixties, another decline in the seventies, and the principal maximum of the century in the eighties.

The 1903 floods in Kansas and Missouri covered substantially the same region, although one less in geographic extent than the 1844 flood. The crests reached in the later flood fell about 3 feet short of the 1844 flood, but it seems clear that the meteorological conditions were very nearly repeated after the lapse of 59 years.

The 1915 floods[4] in the same districts come under the same category as those first named. There have been, therefore, a recurrence within historic times of substantially the same rain producing floods in the Kansas-lower Missouri watershed at two intervals of 59 and 12 years, respectively.

The meteorological conditions associated with the greatest flood on the Connecticut can be inferred quite accurately from the weather notes that have been preserved. It is quite probable that an area of high pressure and unseasonably low temperature moved into the St. Lawrence Valley and northern New England immediately preceding the rains, and that a weak cyclonic system persisted for several days over, say, the mouth of the Hudson. The relative position of the HIGH and the LOW would give southeast winds and rain over Connecticut and snow over the upper portion of the watershed. Maximum temperatures of 80 degrees were recorded on three days preceding the storm. These high temperatures doubtless melted all of the old snow remaining in the mountains of New Hampshire and Vermont and filled the streams bankful, and it was on streams thus swollen that a 66-hour rain descended on the lowlands and a foot of wet snow on the mountains. By reason of the prevailing temperature the greater portion of the snow water, reached the stream and on account of the duration of the rainfall the run-off from the latter must also have been very great. The flood seems to have been greatest on the lower reaches of the river since the stage at Holyoke, Mass., was exceeded by the flood of October, 1869, 15 years later.

In any event the occurrence of the greatest flood of 300 years in New England seems to have been due to a particular combination of meteorological conditions, viz, the juxtaposition over New England of low pressure and high pressure at a time of year, and in such relative position, as to cause continued and heavy precipitation for 66 hours. No like combination has presented itself since that time, although a somewhat similar combination was present in October, 1869. At that time of year there was no snow to augment the run-off and the streams were not at a high stage.

As illustrating the rule that even great floods are a more or less local phenomenon Table 3 has been prepared. Compare for example the records for Pittsburgh and Cincinnati, both on the Ohio River.

TABLE 3.—*Year of occurrence of great floods at the places named.*

Station.	Order of magnitude of floods, Nos. 1 to 11, inclusive.										
	1	2	3	4	5	6	7	8	9	10	11
Hartford, Conn.	1854	1862	1843	1869	1896	1859	1841	1913	1901	1895	1902
Lawrence, Mass	1896	1852	1870	1895	1901	1878	1869	1902	1862	1859	1877
St. Louis, Mo	1844	1903	1892	1909	1908	1883	1881	1904	1917	1882	1876
Cincinnati, Ohio	1884	1913	1883	1907	1918	1898	1897	1901	1890	1832	1899
Pittsburgh, Pa	1907	1884	1902	1913	1891	1861	1908	1862	1904	1897	1860 1905
Chattanooga, Tenn.	1867	1875	1886	1917	1884	1890	1918	1902	1896	1882	1899
Nashville, Tenn.	1882	1890	1918	1884	1886	1874	1891	1897	1913	1912	1880
Augusta, Ga	1908	1888	1912	1891	1913	1918	1887	1902	1903	1889	1892
Little Rock, Ark	1844	1876	1872	1877	1892	1904	1898	1916	1884	1885	1908
Kansas City, Mo	1844	1903	1908	1915	1909	1917	1881	1904	1892	1883	1907

EUROPEAN RIVERS.

Naturally one turns first of all to the Danube, a river rich in historical associations, with a history covering a span of more than a thousand years. Unfortunately the flood record for this stream consists of an almost endless recital of floods beginning in the eleventh century and ending with two disastrous rain floods at the end of the nineteenth century. It is quite impossible to class the floods according to magnitude, except as indicated in the next paragraph. In passing, it may be remarked that systematic gagings of the Danube began in 1826.

The following note appears in a chronological statement of floods in the Danube.[5]

> Among the old high-water marks on the Danube stone bridge at Vienna, that of February 26, 1830, takes the highest place, followed by those of February 14, 1776, February 13, 1795, February 24, 1799, March 19, 1740, January 21, 1880, February 4, 1862 (ice free), July 18, 1736 (ice free), and March 5, 1803. Of the marks within recent times, those of September 17, 1899, February 10, 1893, August 2, 1897, January 3, 1883, and June 9, 1892, stand in the seventh, eighth, ninth, tenth, and eleventh positions, respectively, and that of September 5, 1890, in last place.

[4] MONTHLY WEATHER REVIEW, 44: 287.

[5] Report of the Central Bureau of the Austrian Hydrographic Office, Engineer Ernst Lauda, on the "High Water Catastrophe of 1899."

The record here covers 15 floods within a period of 178 years. The total number of great floods in the Danube in the nineteenth century was 10, a greater number than on any other European river examined.

My disappointment in the flood record of this stream is lessened somewhat, however, by the fact that there is no river in North America that parallels it in many of the essential features which produce floods. The source of the Danube is at an altitude of about 2,100 feet, and in north latitude 48° 30′ to 49°. It flows thence east-southeast, receiving the flow of many mountain tributaries, and after pursuing a tortuous course for about 1,730 miles, empties into the Black Sea in latitude about 45°. Were we to superpose the course of the Danube upon a map of the continent of North America, its source would lie in Manitoba and its mouth in the neighborhood of Eastport, Me. By reason of its high latitude and the mountainous character of its upper watershed, the spring break-up of the ice is the prime cause of destructive floods. The occurrence of two very destructive rain floods, viz, those of July–August, 1897, and September, 1899, is described in two memoirs of the Austrian Hydrographic Bureau issued in 1900. The closeness of the net of rainfall and river-gaging stations in Austria makes it possible to present the details of the flood phenomena with a fullness that is greatly appreciated.

The direct cause of the September, 1899, flood, said to have been the greatest *rain* flood of a century, was a six-day period of constant and rather heavy rains over a strip of country about 250 miles long and 100 miles wide. The volume of the precipitation over the watershed of the Danube above the mouth of the March River, area about 40,000 square miles, was nearly 16 cubic kilometers, not so great as in the March, 1913, floods in the Ohio Valley. It is interesting to note that this heavy precipitation was due to the slow movement of a large cyclone that persisted over lower Austria from September 8 to 14, 1899.

THE SEINE AT PARIS.[6]

Systematic gagings of the Seine at Paris extend back to 1649. During the 271 years that have elapsed since that time, there has been one great flood and many lesser floods. Curiously, the record flood of the period was made in 1658—but nine years after the beginning of observations, the nearest approach to that flood in subsequent years was in January, 1910, when the stage fell 1 foot short of that of the 1658 flood. I have tabulated the Seine floods exceeding 20 feet on the La Tournelle Bridge at Paris from 1649 to 1919. These floods number 22, distributed as follows: Seven occurred in the last half of the seventeenth century, seven each in the eighteenth and nineteenth centuries, and a single great flood has occurred thus far in the twentieth century, and at this time the second great flood of the twentieth century at Paris is prevailing.[7] The table follows:

Floods above 6 meters (19.68 feet) in the Seine at Paris, 1649–1918.

	Feet.
February, 1658	28.9
January, 1910	27.9
December, 1740	25.9
January, 1650	25.5
February, 1649	25.2
March, 1711	24.9
April, 1690	24.6
January, 1802	24.2
June, 1697	23.9
March, 1844	22.9
February, 1764	22.6
February, 1799	22.6
March, 1751	21.9
March, 1784	21.9
March, 1807	21.9
February, 1679	21.5
March, 1876	21.3
June, 1693	21.3
December, 1836	21.0
March, 1817	20.6
December, 1801	20.3
February, 1784	20.3

From the record of the Seine floods, the following inference may be drawn. In a long series of observations the number of great floods per century is substantially the same. The intensity, however, varies from one century to another, and there appears to be a tendency to occur in groups rather than singly and at widely separated intervals. The interval in years between great floods does not seem to bear any relation to the intensity of successive floods.

In passing, it should be noted that three extraordinary floods occurred at Paris in the space of nine years—1649 to 1658—whereas in the succeeding centuries the interval was always much greater.

RIVERS OF GERMANY.[8]

In general, river gagings for German rivers are not available, except for a few localities, before the nineteenth century. The record for the nineteenth century, however, seems to be complete.

The Neckar.—The highest water of the nineteenth century on the Neckar was reached in the year 1824, with a gage height at Diedesheim of 1,074 centimeters above zero. Other important floods on that river during the same century, arranged in the order of their magnitude, were:

	Centimeters.
1824	1,074
December, 1882	845
March, 1845	804
February, 1850	780
August, 1851	717
February, 1862	711
January, 1834	705
March, 1896	589

In all, 8 great floods.

The Main at Frankfurt.—The highest water of the nineteenth century was reached at Frankfurt-on-Main in March, 1845, gage height, 728 centimeters; other floods were:

	Centimeters.
December, 1882	728
November, 1882	706
February, 1862	648
February, 1876	632
February, 1850	610
March, 1831	610
January, 1841	583

In all, 8 great floods, as on the Neckar.

The Rhine at Coblenz.—The greatest floods of the nineteenth century in the Rhine at Coblenz were in March–April, 1845, November–December, 1882, and December–January, 1882–83; gage heights, 920, 913, and 834 centi-

[6] Manuel Hydrologique du Basin De La Seine, Paris, 1884.
[7] New York Times, Jan. 3, 1920.

[8] Der Rheinstrom: Baden Central Bureau Fur Meteorol. und Hydrographie, Berlin, 1889.

meters, respectively. Other floods in the same century were:

	Centimeters.
December, 1819	834
March, 1844	811
March, 1876	811
November, 1824	790
February, 1862	787
December–January, 1833–34	774
March, 1855 (ice flood)	685
March, 1896	—

In the early centuries extraordinary floods in the Rhine at Cologne are said to have occurred as follows:

In summer of 1342.
In February, 1374 (ice free).
In winter of 1425.
In 1432 (ice flood, 1,033 centimeters?).
In winter of 1490–91.
In summer of 1491.
In winter of 1497–98 (ice free).
In January, 1552.
In March, 1563.
In March, 1565.
In March, 1571.
In March, 1573.
In March, 1595 (884 centimeters).
In January, 1651 (ice flood, 923 centimeters).
In March, 1651 (927 centimeters).
In March, 1658 (949 centimeters).
In March, 1740 (ice flood, 933 centimeters).
In January, 1758 (790 centimeters).
In February, 1784 (ice flood, 1,263 centimeters).

This list contains a reference to 19 great floods, of which the probable gage heights of 8 are given. Comparing these gage heights with the gage height of the absolute maximum flood at Cologne for the nineteenth century, it is noted that but two floods in 190 years were greater, viz, those of January, 1758, and February, 1784. The last named, with a gage height of 12.6 meters above zero of the gage, seems to have been the greatest flood on the Rhine at Cologne during the period 1342–1900. It was, however, an ice flood, and must therefore be placed in the category of winter floods intensified by ice conditions.

DISCUSSION.

By ROBERT E. HORTON.

(By letter.)

I have found, as I stated at the meeting, a similar constancy between the maximum and the average precipitation per rainfall day, at numerous stations in the United States, regardless of what the mean annual precipitation might be. I have also found the frequency of occurrence of large amounts of rain per rainfall day, of large total amounts in individual storms, and of large amounts in short-time intervals, as for example, 5 to 60 minutes, and in many cases the frequency of occurrence of maximum floods may all be very satisfactorily represented by an expression of the form:

$$\frac{\phi_1}{\phi_a} = A - b\epsilon - ct^n$$

in which ϕ_1 is the magnitude of an event having average interval of occurrence t, and ϕ_a is the average magnitude of the event. The frequency curve for the determination of the constants in the formula is very readily derived by simply arranging the events in their order of magnitude, and computing the average intervals from the observations. For example, the greatest flood observed in a 50-year record is taken as having an average recurrence interval of 50 years, the second greatest 25 years, etc. Now, the peculiar advantage of this method of study seems to be that whereas maximum events do not occur with sufficient frequency so that their average intervals of recurrence can be accurately determined or estimated from a consideration of the maximum alone, this method of plotting and study makes it possible to derive a curve and usually a very good one, based mainly on events of the same kind, of much more frequent occurrence. In other words, the law of frequency is determined mainly from events well below the maximum. A peculiarity of these curves is that they are practically never parabolic. They can not be represented by straight lines on logarithmic cross-section paper, nor by direct plotting on semilogarithmic paper. Consequently they are not ordinary logarithmic curves, as Fuller assumes in deriving his flood formula. They are, however, well represented by an expression of the type above given. It will be noted that this expression approaches a limit of the value of $\phi_1 = a$ as the recurrence interval t approaches infinity; in other words, it leads to the conclusion that most natural events dependent on rainfall can be represented by frequency curves approaching a certain maximum value as an asymptote, and the method of plotting which I have described makes it possible to determine the position of the absolute maximum or limiting value with considerable accuracy, and without placing any great dependence on meager observations of values near the maximum.

The fact that there is a maximum flood stage for any given stream which is never transcended seems apparent. The cause of this physical limitation of hydrologic events dependent on rainfall is also apparent. Actually, it seems to me that the causes contributing to flood magnitudes are so diverse and numerous that their operation may be, for practical purposes, considered fortuitous, in a particular sense, just as the causes which determine which particular face of a dice will come uppermost are so numerous and complicated that the actual result is what we call "a result of chance." But there is a limit in both cases. In throwing a dice, the highest number which can be thrown is 6. A better illustration is obtained by considering the effect of throwing together several dice, say 100. The greatest number which can possibly be thrown is 600. The chance of throwing other numbers less than 600 is not, however, equal, because there are many ways in which some smaller numbers may be thrown, whereas there is only one combination that produces 600.

Similarly, in the case of floods, the combination of causes which can produce an absolute maximum flood is very much more limited than the number of combinations which can produce an ordinary flood; in fact, it seems to me that the occurrence of increasing magnitudes of such events is essentially of the nature of a phenomenon of exhaustion. The larger the magnitude, or the greater its departure from the average magnitude of the event, the greater is the difficulty of its occurrence. The difficulty of occurrence, to use a nontechnical expression, of an event of large magnitude apparently increases in about a geometric progression as the magnitude increases in an arithmetical progression. In other words, the law is similar to ordinary laws of exhaustion applying to various physical phenomena.

This affords a semirational explanation of flood frequency formula, as above given. Now as the duration of a record increases, the maximum event or magnitude increases approaching the limit, and the average value of the event approaches the true mean as a limit. Since the two values are constant, their ratio is constant for a given stream; in other words, the ratio ϕ_1 to ϕ_a approaches a constant limiting value as the duration of the record increases.

Now, for different streams in the same region, the causes which operate to produce floods operate in the same way, but in different degrees both for different streams, and for different floods of the same stream. Apparently any condition which tends to increase the maximum flood stage increases the average flood state in about the same degree, consequently the limiting values of the ratios of ϕ_1 to ϕ_a may be very nearly the same for different streams in the same region.

THE RELATIONS OF WEATHER AND BUSINESS.[1]

By ARCHER WALL DOUGLAS, Simmons Hardware Co., St. Louis.

[Excerpts.]

Agriculture is, and probably will be for generations, the main business of this country and the main foundation of its continuing welfare. Agriculture is largely dependent upon the weather for its results, especially in those sections and States west of the Mississippi River, where the annual precipitation sometimes varies from 10 inches to 30 inches. Obviously, any intelligent and reasonably accurate long-distance forecast of the probability of weather happenings will be of incalculable value to the business world in such States and sections, seeing that all business in such regions hangs largely upon the results of agricultural production. * * * Such a forecast, in the present state of our knowledge of the weather can not possibly be absolutely accurate, as everyone would certainly, even though unreasonably, expect it to be. * * *

[Some attempt at such a forecast] has been essayed by the committee on statistics of the Chamber of Commerce of the United States, as set forth in their two bulletins, "The Relations of Business and Weather in Relation to Rainfall" and "In Relation to Temperature" [1919]. The general method followed in this investigation, extending over a long number of years, concerned itself as much with personal travel and study in every section of the country as with mere analysis of figures. For instance, the observer learned that two most important features of the effects of drought upon growing plants, especially corn, in the Great Plains States are as to whether such droughts were marked by the presence or absence of exceedingly high temperatures and hot winds. * * *

The basis of the two bulletins of the committee on statistics is [that] the weather has a tendency to recur in the way of the extremes of heat and cold, rainfall, and the lack of it. Also, in common with most other things in nature, that the same kinds of seasons have a tendency to flock together in the way of the association of dry years with dry years and wet years with wet years for a comparatively brief period. There are unexpected exceptions to this tendency, but in an experience of a number of years this general statement has proved to be fairly reliable for business purposes in from 75 to 80 per cent of the time—which of course is rather better than guessing or trusting to that rather absurd law of averages in such a case, or consulting the wishbone of the goose or a local almanac. * * * So it was perfectly immaterial for the purposes of practical business, whether the theory proved mathematically correct when it indicated, some months in advance, the mild open weather of the winter of 1918–1919 and the wet spring and summer of 1919 for the locality of St. Louis and vicinity; also the comparatively colder autumn of 1919 as compared with the similar period of 1918.

[In the southern Great Plains, which for two or three years previous to 1919 suffered from severe drought, and in the northern Great Plains, where a long drought ended in the fall of 1919, it is reasonable to expect relatively favorable conditions in 1920.]

Let us consider the value of a possible forecast of the weather, some months hence, in relation to the sale of what are known as seasonable goods, namely, goods which sell only at certain seasons and then because of the prevalence of certain kinds of weather. Lawn mowers, for example, in wet weather because grass grows best then, and rubber hose naturally sells best in dry weather. These goods have to be made up by the manufacturer and contracted for by the distributor many months in advance of their actual use by the consumer. Whether the weather be wet or dry very seriously affects the sale of both of the lines. Now, suppose a distributing house handling both lawn mowers and rubber hose wished to find out in August, 1918, about how they should order these goods for the coming season of 1919 compared with their sales in the season of 1918 just past. The theory I have spoken of forecast very definitely a wetter spring and summer in 1919 than in 1918 in the vicinity of St. Louis, and that is exactly what happened. Now, suppose this same house wished to know in February, 1919, what kind of an autumn and winter 1919–20 would prove, as to temperature and snowfall, as compared with the similar season of 1918–19, as affecting the sales of ice skates and snow shovels. The theory answers, a somewhat colder autumn and winter and rather more snow. Now, these incidents are the stories of actual happenings. It needs only a little thought to have you realize the far-reaching benefit to business of any system of weather forecasting which will indicate, if only approximately, what kind of weather may be expected in the near future. * * *

DISCUSSION.

Prof. A. E. Douglass called attention to the fact that the recent drought in the southwest was the worst since 1821.

Mr. A. W. Douglas showed that the climate in the southwest has not changed, but that after two or three years of unusual rainfall a dry year may be expected. Business men in that region, however, have gone on preparing for more wet years.

Prof. J. Warren Smith mentioned that a tabulation of 35 winters in Ohio have indicated, as Mr. Douglas had pointed out, that the general character of a winter could be determined by probability.

Prof. H. J. Cox said that the studies of Mr. Douglas are rather more of probabilities than meteorology, and inquired if there is any reason to suppose that a warm winter will follow a warm one.

Dr. C. F. Brooks replied that these changes in the character of the winter are controlled by centers of action, and if, in turn, through such studies as those of ocean temperatures, the general forecasting of the location of such centers of action can be accomplished, the general character of the season can be forecast with more basis than simple probability.

Dr. F. L. West remarked that the prospective purchaser of a water power plant in Utah inquired concerning the relation of the rainfall of the last 10 years to the 35-year mean and found that it had been 25 per cent in excess of normal, whereupon he was somewhat skeptical regarding his purchase, since the succeeding years would probably not yield so much water power.

[1] Presented before American Meteorological Society, St. Louis, Mo., Dec. 30, 1919.